

## **Stellar and Binary Evolution in Star Clusters**

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Final Report

This document is the final report on research activities performed under NASA Astrophysics Theory Program Grant NAG5-6964 ("Stellar and Binary Evolution in Star Clusters") between April 1998 and March 2001.

### **Overview of Scientific Results**

Under this grant, substantial progress was made in the development and dissemination of the "Starlab" software environment. In collaboration with P. Hut (IAS), J. Makino (Tokyo University), and S. Portegies Zwart (MIT/ University of Amsterdam), significant improvements were made to "kira," an N-body simulation program tailored to the study of dense stellar systems such as star clusters and galactic nuclei. Key advances include (1) the inclusion of stellar and binary evolution in a self-consistent manner, (2) proper treatment of the anisotropic Galactic tidal field, (3) numerous technical enhancements in the treatment of binary dynamics and interactions, and (4) full support for the special-purpose GRAPE-4 hardware, boosting the program's performance by a factor of 10-100 over the unaccelerated version. The data-reduction and analysis tools in Starlab were also substantially expanded.

A Starlab Web site (<http://www.sns.ias.edu/~starlab>) was created and developed. The site contains detailed information on the structure and function of the various tools that comprise the package, as well as download information, "how to" tips and examples of common operations, demonstration programs, animations, etc. All versions of the software are freely distributed to all interested users, along with detailed installation instructions.

McMillan and collaborators have applied Starlab to a variety of problems in star cluster evolution. Applications include a survey of cluster lifetimes in the presence of various realistic assumptions about stellar mass functions and external Galactic fields (with graduate student Kimberly Engle), and studies of the evolution of very young dense star clusters, such as 30 Doradus in the LMC and the Arches and Quintuplet systems in the Galactic Center (with Portegies Zwart, Hut, and Makino). McMillan and Portegies Zwart used Starlab to calibrate a study of the formation and merger rates of black-hole binaries.

Their main finding, that black-hole mergers could be very important sources of LIGO events, caused considerable excitement in the Relativity community. In addition, McMillan and Portegies Zwart completed the first ever full-scale simulation of the evolution of an open cluster (the Hyades), with primordial binaries, a Galactic tidal field, and stellar and binary evolution all included in a self-consistent manner. A series of papers studying the evolution of young star clusters in the Galactic center and the possible collisional formation of intermediate-mass black holes in dense stellar systems has been initiated.

An ongoing collaboration with the “Virtual Director” visualization groups at the National Center for Supercomputer Applications (D. Cox, S. Levy), and the Hayden Planetarium at the American Museum of Natural History (N. Tyson, M. Shara, B. Abbott) has resulted in the development and distribution of the “partiview” display tool, an interactive visualization program that allows users to fly through evolving N-body datasets in real time. Partiview is fully integrated with Starlab, and runs on platforms as diverse as laptops, Cave displays, and the Hayden Planetarium dome.

## **Personnel**

Drexel graduate student Engle successfully defended her Ph.D. thesis in the Spring of 1999. Postdoctoral research associate Xiaolan Huang, from Cornell University, worked with McMillan from February 1999 until December 2000. Her Fokker-Planck studies complemented the direct N-body approach used in Starlab, centering on a Monte-Carlo treatment of binary dynamics in evolving star clusters. The work was reported at the Atlanta AAS meeting in January, 2000, and at the “STAR 2000” meeting in Heidelberg in March, 2000.

## **Publications**

These projects have resulted in publications in *Astronomy and Astrophysics*, *Astrophysical Journal*, and *Astrophysical Journal Letters*, as well as numerous conference proceedings, as follows.

S. F. Portegies Zwart, J. Makino, S. L. W. McMillan, and P. Hut. *The Lives and Deaths of Star Clusters Near the Galactic Center*. *Astrophysical Journal*, 565:265-279, 2002.

T. Ebisuzaki, J. Makino, T. G. Tsuru, Y. Funato, S. Portegies Zwart, P. Hut, S. McMillan, S. Matsushita, H. Matsumoto, and R. Kawabe. *Missing Link Found? The “Runaway” Path to Supermassive Black Holes*. *Astrophysical Journal Letters*, 562:L19-L22, 2001.

S. F. P. Zwart, S. L. W. McMillan, P. Hut, and J. Makino. *Star Cluster Ecology - IV. Dissection of an Open Star Cluster: photometry*. *Monthly Notices of the Royal Astronomical Society*, 321:199-226, 2001.

S. F. Portegies Zwart, J. Makino, S. L. W. McMillan, and P. Hut. *How Many Young Star Clusters Exist in the Galactic Center?* Astrophysical Journal Letters, 546:L101-L104, 2001.

S. F. Portegies Zwart and S. L. W. McMillan. *Black Hole Mergers in the Universe.* Astrophysical Journal Letters, 528:L17-L20, 2000.

S. F. Portegies Zwart, J. Makino, S. L. W. McMillan, and P. Hut. *Star Cluster Ecology. III. Runaway Collisions in Young Compact Star Clusters.* Astronomy and Astrophysics, 348:117-126, 1999.

S. F. Portegies Zwart, P. Hut, J. Makino, and S. L. W. McMillan. *On the Dissolution of Evolving Star Clusters.* Astronomy and Astrophysics, 337:363-371, 1998.

S. L. W. McMillan, C. Pryor, and E. S. Phinney. *Binaries in Globular Clusters.* Highlights in Astronomy, 11:616, 1998.

X. Huang and S. L. W. McMillan. *A Hybrid Fokker-Planck / Monte-Carlo Code For Globular Cluster Evolution.* In ASP Conf. Ser. 228: Dynamics of Star Clusters and the Milky Way, page 449, 2001.

P. J. Teuben, P. Hut, S. Levy, J. Makino, S. McMillan, S. Portegies Zwart, M. Shara, and C. Emmart. *Immersive 4-D Interactive Visualization of Large-Scale Simulations.* In ASP Conf. Ser. 238: Astronomical Data Analysis Software and Systems X, volume 10, page 499, 2001.

S. Portegies Zwart and S. L. W. McMillan. *Merger Rates of Black-Hole Binaries: Prospects for Gravitational-Wave Detectors.* In Black Holes in Binaries and Galactic Nuclei, page 252, 2001.

S. L. W. McMillan and S. F. Portegies Zwart. *Black Hole Mergers in the Universe.* In ASP Conf. Ser. 228: Dynamics of Star Clusters and the Milky Way, page 517, 2001.

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